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Temperature Control of Hot Isostatic Pressing (HIP) Furnace Using Model Predictive and Risk Sensitive Optimal Controllers*

by

Raman K. Mehra, Shah Mahmood & Joe Runkel↑

Abstract: Fabrication of Metal Matrix Composites (MMC) requires the use of sophisticated manufacturing processes. One such process is Hot Isostatic Pressing (HIP) which is becoming a key technology for manufacturing MMC airframe structural panels for advanced aircrafts, superalloys and titanium alloys. We present in this paper the results of applying modern control techniques such as Model Predictive Control (MPC) to HIP furnaces to achieve optimal temperature and pressure profiles - this would minimize the ultimate cost per unit of production. A HIP furnace is primarily a non-linear distributed parameter process. The problem was solved in three steps. First, a nonlinear physical model was developed and validated from experimental data from a real 3-zone HIP furnace located at Industrial Materials Technology (IMT), Andover, Mass. The model was linearized in the second step to approximate the steady state behavior of a HIP furnace. Finally, in the third step, the linear model was used to design an MPC controller. Another control technique similar to H-infinity known as Risk Sensitive Optimal (RSO) control was used in combination with MPC to increase robustness and improve steady state regulation. The controllers were tested on the nonlinear simulator. The response time of the combined MPC-RSO controlled system was less than one-third of the closed loop time response of the system under current PID control. The combined controller was also found to attenuate low frequency disturbances to a satisfactory level.

1. Introduction

Hot Isostatic Pressing (HIP) is a key technology for the processing of advanced aerospace materials including MMC's, superalloys, and titanium alloys. Originally HIP technology revolved around carbide cermet and aerospace investment casting densification. The internal porosity in investment castings can be significantly reduced, and often, completely eliminated by application of HIP. Over the years the technology has found numerous applications as a consolidation technique both in power metallurgy and in metal matrix composites (MMC). More recently HIP has evolved into a key enabling technology governing the widespread use of MMC's, and titanium matrix MMCs reinforced with silicon carbide fiber, were produced as panels for the National Aerospace Plane (NASP).

The HIP furnace represents a unique and very demanding control application. Strong upward movement of heat via convection of argon at several hundred to several thousand atmospheres pressure requires multizone furnaces. While PID control can handle steady state rather well, optimum response under transients in temperature and pressure where the physical properties of argon change can only be acheived by advanced multivariable control techniques such as Model Predictive Control (MPC)

Amongst the many approaches of modern control, MPC has achieved great success in process control application. This approch has been implemented under different names such as Model Algorithmic Control (Richalet et. al(1978), Mehra et.al (1977,1982), Rouhani and Mehra (1982)), Dynamic Matrix Control and Internal Model Control (Garcia and Morari (1982, 1989)). More recently, the approach has been extended to nonlinear systems using Nonlinear Programming (NLP) methods (Sistu, Gopinath and Bequett (1992)) and Neural Network models. Soroush and Kravaris (1993) show the Globally Linearizing Cotnrol (GLC) for nonlinear systems can also be obtained from MPC, if the control and state constraints are ignored. MPC can also be implemented using Fuzzy Logic for systems that cannot be described by analytical modes.

This paper is organized as follows. The working principle of the HIP furnace is explained in Section 2. A lumped parameter nonlinear model that is accurate enough for designing a controller is also developed in this section. A brief description of the proposed control technologies viz., MPC and RSO are provided in Section 3. Both of these control techniques are applied to the HIP furnace and the results are described in Section 4. Finally, some conclusions and areas for further research are given

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↑ First two authors are with Scientific Systems Co., 500, West Cummings Park (#3950), Woburn, MA, 01801; email address: shah@ssci.com. The 3rd author is with Ultraclad Corp., Andover, MA

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in Section 5.

2. A Simplified Description of a HIP Furnace

Process Description: A hot isostatic press (HIP) is a pressure vessel which includes a furnace. The pressurization medium is a gas. While the gas may, in theory, be any useful gas, we will restrict our discussion to the use of argon gas. A typical hot isostatic press, "HIP unit or system", is described in Figure 1. The vessel is a monolithic forging of high strength, quenched and tempered, alloy steel; some vessels are also made of thinner walled vessels where the longitudinal stresses are carried by large wire wound or cast iron yokes. The pressure transfer medium of the hot isostatic press is usually argon, at 150°C to 2200°C and 50 to 3000 bar or atmospheres. HIP units range in size from 6 inch diameter by 12 inch long to 76 inch diameter by 144 inches long pressure vessels. The resistive heating elements, usually made of molybdenum, are placed near the walls, while the sensors are located near the heating elements as well as within the load.

The load is heated indirectly via the argon gas by convection transfer and at high temperatures directly by radiation. Within the hot zone, gas will tend to rise as it is heated and its density decreases. Thus the top of the hot zone will tend to heat faster than the bottom. This important phenomenon differentiates HIP systems from other furnaces. In effect heat is transferred vertically upward from the lower heating zones to the upper heating zones. When power is reduced and the the HIP furnace begins to cool, the top and bottom of the hot zone cool at very different rates, again as a result of gas density gradients accommodating temperature gradients. Gas next to the mantle cools first via convective heat transfer. This cool gas falls to the bottom due to its relatively higher density. Pronounced stratification takes place with the bottom of the unit seeming to cool much faster than the top. If one measured time constants of the different regions, the result would be shorter time constants for the bottom zones.

A Lumped Parameter Model of a HIP Furnace:

The observed behavior of the temperature profile of each zone can be modelled by a combination of a resistance R and a capacitance C in a traditional RC circuit as shown in Figure 2. The voltage across the elements then represents the temperature in that zone and the current in the loop represents the heat flow through the region. The voltage (temperature) is denoted by by T(t) and the power (heat) by u(t). When heat is supplied to a zone, part of it is used in that zone to raise the temperature of the zone that depends upon the value of the modelled resistance. The rest, however, flows to upper zones via convection - the heat does not flow to lower zones. The product of R and C i.e. RC determines the dynamic response of the temperature in the zone in response to the heat input. When heat (input $u_1(t)$) is supplied to Zone 1 in the 3-zone furnace, according to the above description, all of it is used in this zone. When it comes to the case of input $u_2(t)$ supplied to Zone 2, a fraction k_{12} of this heat flows upwards to Zone 1 and the remaining $(1-k_{12})$ is utilized in Zone 2. A similar phenomena occurs for input $u_3(t)$ to Zone 3: a part k_{23} of $u_3(t)$ flows to Zone 2 and another fraction (k_{13}) flows to Zone 1. This type of coupling results in an upper triangular input coupling matrix of the system.

The temperature response model can be written in a state space format as follows:

$$\dot{T}(t) = A\,T(t) + B\dot{u}(t) \qquad (2.1)$$

where

$$T(t)=\begin{bmatrix} T_1(t) \\ T_2(t) \\ T_3(t) \end{bmatrix}, u(t)=\begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix},$$

$$A=\begin{bmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{bmatrix},$$

$$B=\begin{bmatrix} b_{11} & k_{12}b_{12} & k_{13}b_{13} \\ 0 & (1-k_{12})b_{22} & (1-k_{12})k_{23}b_2 \\ 0 & 0 & (1-k_{23})b_{33} \end{bmatrix}$$

and T_i (t) = temperature at time t of the i-th zone, I=1,2,3, u_i (t) = power input at time t to the i-th zone, i = 1,2 3, $a_{ii} = 1/R_iC_i$, i=1,2,3, $b_{11} = b_{12} = b_{13} = /C_1$, $b_{22} = b_{23} = 1/C_2$; $b_{33} = 1/C_3$. The input unit is in Kcal/min and the output is in °F. If the input in Kcal/min is multiplied by 0.0698, it becomes the input in KW.

Sources of Nonlinearity: The fractions k_{12}, k_{13}, k_{23} in the model (2.1) are the primary sources of non-linearity in the model. These fractions are

determined by the temperature difference between the two adjacent zones. For example, k_{12} depends upon the temperature difference $\Delta T_1(t) = T_1(t) - T_2(t)$ via a saturation type non-linearity. The other source of non-linearity that must be considered in the control designis that the power input to a particular zone cannot exceed a pre-defined limit. This limit, in turn, depends upon the temperature in that zone. In most cases, this dependence can be approximated by a linear relationship between the zone temperature and the input to that zone.

The model developed above was validated from experimental data from an ***8 inch 3-zone HIP unit*** at Industrial Materials Technology, Andover, Mass. The nonlinear time-varying model described above is linearized around a **nominal value of T=[1200 1000 900]'.**

3. Multivariable Optimal Control Design for HIP Furnance

At present, in most of the installations, HIP furnaces are controlled by traditional PID (Proportional, Integral and Derivative) controllers. Although the closed loop response from these controllers are better than the open loop response, they suffer from many problems. First, these are basically single loop controllers in the sense that each zone of a HIP furnace is controlled independently of the other zones; the interaction between the zones can not be handled easily. Second, there are no easy way to accomodate the nonlinearities, time variations and input constraints in a PID framework. To overcome these problems, we have designed MPC controllers for a HIP furnace. To further increase the robustness of the closed loop control system, the MPC controll was augmented by another control techninique known as Risk Sensitive Optimal Control (Whittle, 1990). This technique uses exponential of the quadratic cost in of the traditional Linear Quadratic Gaussian (LEQ) framework.

3.1 Model Predictive Control (MPC) Technique

The desirable features of MPC are that (i) it is an output feedback controller, (ii) it has attractive robustness properties, (iii) there are clear and transparent relationships between system performance and various design parameters embedded in the design procedure, and (iv) it can handle multi-input multi-output systems and hard constraints, thereby eliminating problems of integrator windup.

There are five basic elements in MPC:

(i) A plant to be controlled with output y(k) and input u(k); (ii) An internal model of the plant having the same input-outpout dimension as that of the actual palnt. The input to the model is u(k) and the output of the model is $\tilde{y}(k)$; (iii) A reference trajectory $y_r(k)$ along which the sytem is desired to be guided to a set point. Usually $y_r(k)$ is a smooth curve initialized on the current output of the actual plant y(k) and ending on a possibly time varying set point s(k); (iv) A user-supplied prediction scheme to predict the future output $y_p(k+i),\ i \geq 1$ of the plant; (v) A quadratic cost functional J(k) based on the error $e(k+i) = y_p(k+i) - y_r(k+i)$ and future input sequence u(k+i-1), i= 1, 2, ...N.

Given (i) - (v), MPC finds an optimal control sequence $\{u^*(k+i-1),\ i = 1,2,\ldots N\}$ by minimizing J over the admissible input sequence Once this optimal control sequence is computed, only the first element $u^*(k)$ is applied to the actual plant. The optimization window is then shifted to the next interval and the steps in (i)-(v) are repeated all over again (see Mehra et.al. (1995) for details).

3.2 Risk Sensitive Optimal (RSO) Control Theory with Exposential of Quadratic (LEQG) Cost Fractional:

RSO/LEQG is a relatively recent technique (Whittle (1990)) which is becoming increasingly popular as a robust control design technique. This theory is an extension of the standard LQG framework that includes an additional parameter related to risk propensity of the designer. This design is accomplished by redefining the cost functional to be exponential of the standard LQG quadratic cost function as follows:

$$\gamma_\pi(\theta) = -(2/\theta)\log(E_\pi \exp(\theta C/2))$$

where C is the standard LQG cost functional, θ is the risk parameter and the expectation is taken with respect to the policy π. When the cost in the LQG problem is modified as above, the new problem is rightly called 'Linear Quadratic Gaussian Problem with Exponential Cost Functional (LEQG)'. Note that when $\theta = 0$, the risk-sensitive LQG reduces to the standard LQG. Therefore the standard LQG may be termed as risk-neutral case of LEQG.

The risk parameter θ can be chosen to

reflect the preferences of the designer about the state of "nature". For example, if the designer thinks that the nature is cooperative, θ is chosen positive. In this case the designer is "risk-prone". On the otherhand, if the designer considers the nature as acting in the opposite direction of his objective, he will take a conservative stand and select a negative value of the parameter. In this case the designer is "risk-averse". Because of incorporating this risk-factor in the control design, it is also known as "Risk Sensitive Optimal (RSO)" control. It has been recently demonstrated that the H_∞-control design technique, which has awoken so much interest in the control community, can be considered as a special case of the LEQG (Glover & Doyle (1988)).

4 Application of MPC and LEQG to HIP Furnace

The following problem was chosen to demonstrate the capability of MPC and LEQG controllers: a 3-zone HIP furnace is at ambient temperature (considered to be at zero initial condition). The temperatures of zone 1, zone 2 and zone 3 needs to be elevated to 1200°C, 1000°C and 900°C respectively above the ambient temperature. It is also desired that there be no overshoot or "ringing" in the response. Conditions will change from convective to generally nonconvective as the furnace heats from ambient to steady state.

Open Loop Response of the Non-Linear Model of the HIP Furnace: The open loop response of various zones of the non-linear model to step input shows that it takes about 150 minutes to go to the steady state values of the outputs, which may roughly be taken as the time-constant of the open loop process. The performance of any controller in a closed loop will be measured against the open loop response.

MPC for the 3-Zone Furnace: MPC was applied to the non-linear model with temperature-dependent input constraints. In all of the applications of this section, saturation-type hard non-linearity function was replaced by a smooth differentiable non-linear function. The results from MPC application are shown in Figure 3. The parameters for the MPC design are also tabulated in the figures. It can be seen from the plots in Figure 3 that, although the temperatures of the first and second zone rises quickly (in 20 minutes), the same for the 3rd zone rises very slowly. The controls are also found to be within the saturation limits. However, the rate of change of the control sequence is not satisfactory. The acuators may not be able to implement this type control sequence. This problem can be alleviated by formulating the optimization problem in terms of control-difference $(\Delta u(k) = u(k) - u(k-1))$ instead of the actual control sequence $\{u(k)\}$. The disturbing part of this design is that the temperatures have not reached the corresponding set points even at the end of 50 minutes.

LEQ Controller for the HIP Furnace: Next, a LEQ controller was designed to control this nonlinear plant. The response is similar to that of MPC - the outputs did not reach the set points within 50 minutes. The time derivative of the control sequence for zone 1 and zone 2 are probably unacceptable.

MPC and LEQ Applied to HIP Furnace: Next, both MPC and LEQ were applied to this nonlinear model in two levels consisting of inner loop and outer loop as shown in Figure 4. LEQ control was first applied to the actual palnt to maintain the zonal temperatures within a prespecified envelope : this is the inner loop. In this example, the envelope was set at ±30° F around the corresponding set points. When any of the zone temperatures were found outside this envelope, MPC controller would be triggered on to act as the outer loop controller. The outer loop in this case consists of the combination of the LEQ controller and the HIP furnace. When all of the zone temperatures reach within the envelope again, MPC controller is switched out of the operation. From this time and onwards, only the LEQ controller remains operational.

The results from application of the combined controller is shown in Figure 5. The first output has exactly reached the setpoint of 1200°F in 7.5 minutes, the other two zone temperatures have reached the set points in less than 30 minutes. Morever, there has been no overshoot in any of the zones and there is no tracking error after it has reached the set points. The improvement over the open loop performance is remarkable - the set point has been reached in less than 1/3rd time required by the open loop process. It can be shown that the set points of 1200°C, 1000°C and 900°C for zones 1, 2 and 3 respectively corresponds to a steady state power input of 9.18 kw, 4.14 kw and 9.33 kw for the respective zones. The combined controller also

needs the same steady state input power as can be seen from the input plot in Figure 5.

5. Conclusion and Future Direction:

The HIP furnace represents a unique and very demanding control application especially from the standpoint of modeling. Strong upward movement of heat via convection of argon at several hundred to several thousand atmospheres pressure requires multizone furnances while PID control can handle steady state rather well, optimum response under transients in temperature and pressure where the physical properties of argon change can only be acheived by advanced multivariable control techniques.

Under the scope of the work reported in this paper, we developed a physically based model of a generic 3-zone HIP furnace which was then used to design a two-level controller: LEQ controller for the inner loop and MPC controller for the outer loop. The combined MPC-LEQ controller: (a) acheived outstanding transient response, reaching new setpoints 3 to 5 times faster than PID alone, with no overshoot under a variety of demainding control scenarios with hard temperature dependent input constraints; (b) by adding LEQ control, the MPC controller maintained the setpoint with no offset; equalling or bettering PID performance; (c) MPC-LEQ controllers would reduce cost of HIP operation by reduction of cycle times through faster heating without danger of overshoot; (d) a combination of the HIP model and the controllers can be used in the design of improved HIP furnaces which will optimize the vertical apportioning of power for fastest heating.

Advanced control methods such as MPC-LEQ and extended levels of control can significantly reduce the process cost function by reducing cycle time, supervisory labor, argon and electrical power consumption. It is therefore recommended that future work should include: (i) Extension of the model and MPC-LEQ controller to include load temperatures; (ii) Extension of the model and controller to system pressures from o to 3000 atmospheres. (iii) Improvement of the model to include radiation effects at very high temperatures. (iv) Nonlinear MPC with shorter sampling times and longer prediction horizon.

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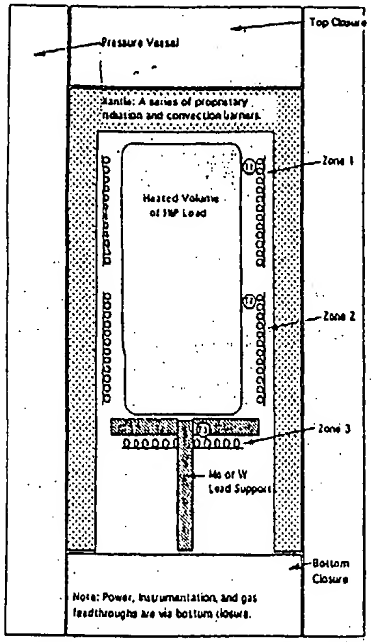

Figure 1: Schematic Representation of a 3 Zone Hot Isostatic Press.

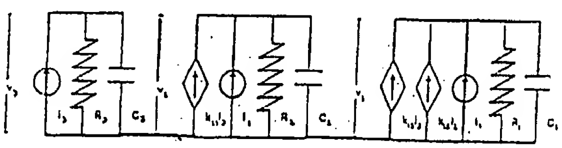

Fig. 2: An Electrical Analog Model of a HIP Furnace.

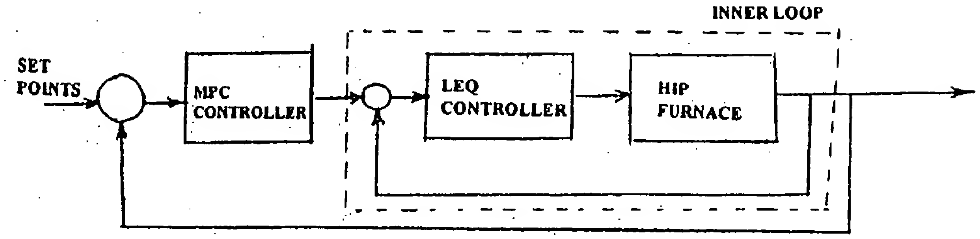

FIG. 4: MPC-LEQ TWO LEVEL CONTROLLER

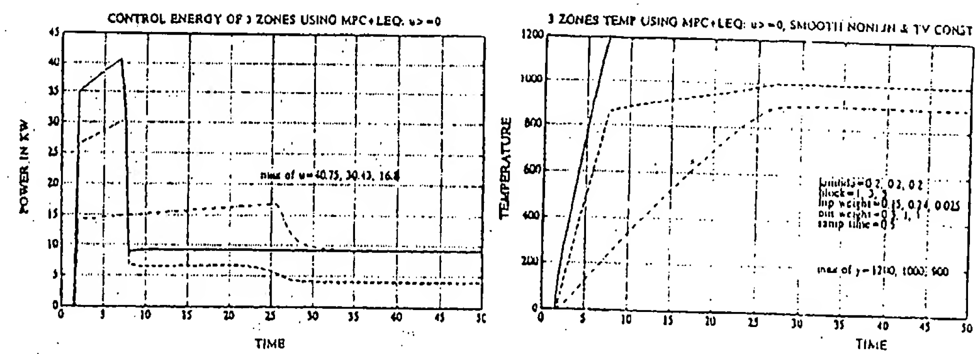

Fig. 5: MPC and LEQ Controller Applied to the 3 Zone HIP Furnace.

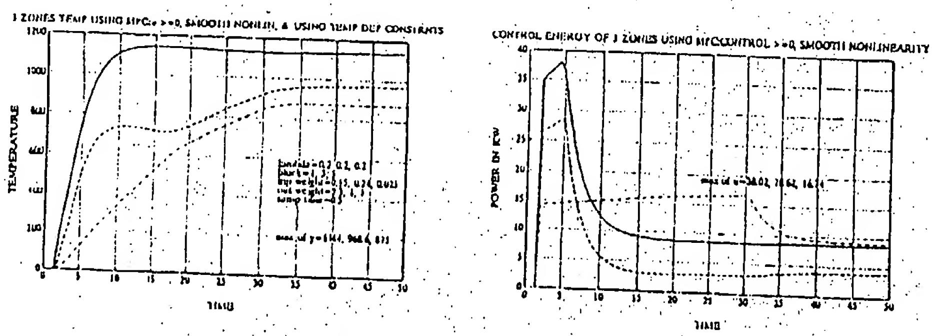

Fig. 3: MPC Controller with Power Constraints.